X-110-70-282

PREPRINT

NASA TM X-65325

PHASED ARRAY ANTENNAS FOR APPLICATIONS ON SPACECRAFT

A. KAMPINSKY
W.H. KUMMER

JULY 1970

GSFC — GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

X-110-70-282

PHASED ARRAY ANTENNAS

FOR APPLICATIONS ON SPACECRAFT

A. Kampinsky
Advanced Plans Staff
Office of the Director

W. H. Kummer
Hughes Aircraft Co.
Culver City, California

July 1970

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

PHASED ARRAY ANTENNAS
FOR APPLICATIONS ON SPACECRAFT*

A. Kampinsky†

and

W. H. Kummer‡

ABSTRACT

Phased array antenna systems, now operating on spacecraft, are reviewed so as to reveal their basic techniques of beam formation, steering and receive/transmit (transponder) functions. Laboratory developmental antennas, designed for ultimate spacecraft flight qualification, are assessed in terms of the needs of Communications, Earth Resources Instrumentation, and Area Surveillance Programs.

---

*Published in Proceedings of the 1970 Phased Array Antenna Symposium, 2-5 June 1970, Farmingdale, N. Y.; Sponsored by Polytech. Institute of Brooklyn, MIT Lincoln Lab, Adv. Ballistic Missile Defense Agency, U. S. Army.

†NASA/Goddard Space Flight Center, Greenbelt, Maryland.

‡Aerospace Group, Hughes Aircraft Company, Culver City, California.

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

TABLES

PHASED ARRAY ANTENNAS FOR APPLICATIONS ON SPACECRAFT

INTRODUCTION

The antenna designer has a myriad of antennas to choose from in his search to find a type that will satisfy the required radiation characteristics from a spacecraft. Many parameters constrain the design of an overall satellite system; thus any antenna system chosen will incorporate many compromises. Prime parameters include the following: type of spacecraft stabilization, type of orbit, antenna coverage, volume available, weight, power consumption, reliability, gain, and number of independent links. Factors such as sidelobe levels, beam agility, wide scan angle in two planes, and tracking accuracy play secondary roles in most applications for communications, but may be emphasized for applications to surveillance and instrumentation.

Improvement in system performance could be achieved if high-gain antennas were used. High gain, however, implies a beam from the satellite antenna which may be narrower than the total required coverage region. Therefore, increasing the antenna gain introduces a new requirement, that of steering the narrow beam to a desired portion of the coverage region. The degree of pointing accuracy required increases as the gain is increased. The following two limitations are encountered in steering the beam: first, there is a limitation in the capability of controlling the attitude of a satellite, and second, there is some uncertainty in measuring its attitude at any given time. The first limitation means that very narrow beams would have to be steered continuously to maintain the desired pointing direction as the satellite attitude changes. The second limitation introduces some uncertainty as to exactly where to point the beam with respect to the satellite. In addition, a question also exists of the extent to which the satellite attitude should be controlled in any particular mission. From these remarks, it is evident that antenna gain, beam steering requirements, and satellite orientation control requirements are closely interrelated. Thus, the implications of increased gain are so important that a consideration of antenna techniques must be a part of any overall system design for a mission. The characteristics of these techniques, both electrical and mechanical, form essential parts of tradeoffs in system weight, accuracy, and reliability. For a particular mission, practical compromises must be made. These will depend on the techniques available for directing or steering the antenna beam as compared with those for controlling the vehicle attitude.

Mechanically steered antennas have had a long history of application to space vehicles, thus this paper will be restricted to a review of electronically steered arrays. Several of the arrays to be discussed are complete transponder systems

and their merit has to be judged as complete satellite transponders and not as antennas alone, when weighed against discrete systems in terms of their total power, weight, volume, and reliability. In the next several sections, applications of phased arrays to communications, despun beams, earth observation, and instrumentation will be discussed.

ARRAYS FOR MULTI-CHANNEL COMMUNICATIONS

Particularly for communications, the need is for high gain antennas that allow simultaneous access to multiple small users that are spatially dispersed. Applications include data relay satellites, navigation and traffic control satellites, and broadcast satellites. Such accommodations are incompatible with spacecraft attitude steering and preclude mechanically actuated antennas. Laboratory demonstration antennas, fulfilling such requirements, now operate on two beam formation principles—the all electronic, self-steering, pilot-beam controlled array, and the discrete beam (matrix or lens and feed) array. Both of these systems are applicable to communications and earth resources survey instrumentation which can be carried on NASA Applications Technology Satellites (ATS) F&G, Data Relay Satellite, and Earth Resources Spacecraft, as examples, or on any three-axis-stabilized spacecraft.

It was pointed out in the introduction that the formation of high-gain beams requires the simultaneous consideration of steering them. There are two generic types as follows: those that require external controls to phase the elements properly, and those that are self-steering. The externally controlled systems, such as the conventional phased arrays, need external commands to program the scan controller and a phasing network to form and point the beam in the appropriate direction toward the user. The attitude of the satellite array with respect to the location of the user is a parameter needed by the command system. In the self-steering or adaptive system, electronic circuitry senses the phase of incoming signals to phase the array elements.

Self-Steering Systems

Self-phasing arrays use phase inversion by mixing in order to obtain the required aperture phase progression. The systems used to accomplish the phase inversion may have a variety of forms, each with particular advantages in a given situation. One of the simplest circuits (References 1 and 2) is shown in Figure 1. The basic operating principle may be seen from this figure; the phase of the incoming signal is inverted at each element by the mixer (M) to create the condition necessary for retransmission of a signal back in the direction from which the signal came. Information may be modulated on the local oscillator signal to be sent back in the desired direction. In actual practice, it is simpler to

obtain large amplifier gains and to perform some of the filtering functions at intermediate frequencies rather than at the radio frequencies.

X-Band Repeater. An engineering model of a self-steering repeater for satellite-to-earth communications has been designed, fabricated, and tested (Reference 3). The system is designed as a relay station between any two pairs of ground stations that lie within a 30-degree cone of coverage. The satellite vehicle is assumed to be in a synchronous orbit and to be gravity gradient stabilized with a ±5 degree uncertainty in attitude.

The system has two independent FM/FM channels, each receiving in the 8-GHz band and transmitting at 7.3 GHz. Each channel has an RF bandwidth of 125 MHz. The repeater will steer four independent high-gain beams (two for receiving and two for transmitting) along arbitrary directions within the ±15-degree coverage angle. The positions of the beams are controlled by the phase information obtained from CW pilot signals generated by the communicating ground stations. The function of the pilot signals is to supply the phase information at each receiving antenna element. In systems where a carrier is always present it can be used as the pilot signal. The power and bandwidth in the pilot signals is made small compared to that in the information band so as to conserve overall transmitter power from the station generating the pilot. In all the discussions CW pilots will be used. In an actual system these pilots will be appropriately coded so as to reduce RFI and the redirection of the beams in unwanted directions. Beam designations and the frequency bands utilized are illustrated in Figure 2.

For the data channel of the system shown in Figure 3, a receiving pilot, a transmitting pilot, and a modulated signal are received by the receiving element, passed through a high-pass filter, down-converted to an intermediate frequency, and amplified by a wideband IF preamplifier. After preamplification, the information signal and the pilots are separated by means of a triplexer filter. The pilots then are down-converted to a second intermediate frequency to allow utilization of very-narrow-band bandpass filters to establish a good signal-to-noise ratio for the pilots. These bandpass filters comprise the quadruplexer which, in addition to limiting the noise bandwidth of the pilot channels, serves to separate the pilot signals. After the pilot signals pass through the quadruplexer, they are up-converted to about 200 MHz to enable them to be mixed with the wideband modulated signals without overlap of the power spectra.

With reference to Figure 3, the modulated signals, 450 to 575 MHz, pass from the triplexer to a wideband mixer.* The receiving pilot signal, 206 MHz, also passes to this mixer. If these two signals are mixed and the lower sideband

*The other information band, 675-800 MHz, is processed similarly.

retained, the phase of the resultant IF signal is independent of the relative phase angle of the signals at the elements. The signals from the output of these mixers (one for each element) are in phase and are summed. At the point of summation, the receiving array gain is realized for the information signals.

The signal is then amplified at the intermediate frequency, up-converted to RF and amplified, and then distributed to the final transmitting mixers. At these mixers the transmitting pilot is mixed with the modulated signal and the upper sideband is selected by the bandpass filter that follows. A modulated signal is produced at a transmitting element; this signal has a phase angle that has the opposite sense from the phase angle of the transmitting pilot at the corresponding receiving element. That is the condition necessary to transmit the information from the antenna system in the direction of the transmitting pilot.* In this particular design two arrays were used; one for tran mitting and one for receiving (Figure 4); they were scaled in wavelength to av[illegible] beam squint. For systems operating at lower frequencies with requirements for similar gain, only one array could be used due to limitations on size and weight and problems of stowage in the launch vehicle. The beam squint needs to be removed for widely spaced transmitting and receiving frequencies (Reference 4). Several schemes using electronic circuitry, array scaling, and combinations of both have been proposed for obtaining the proper phase scaling (References 3, 5, and 6).

The system test results were generally satisfactory and are indicative of the performance of a high quality communication channel (Reference 7). Table 1 summarizes the characteristics of the engineering model.

S-Band Repeater. At the present time a small portion of a two-beam, two-channel S-Band phased array based on the principles of the pilot-controlled multibeam array (Reference 3) is being developed using all solid state "micromin" circuitry to obtain an estimate of prime power consumption, weight, and size in terms of electrical performance to be extrapolated for a full array with a gain of 40 db (Reference 6). Each receiving beam and the resultant transmitting beam point toward the user generating the particular pilot. Data are relayed through the self-steering array toward one earth station. Maximum RF bandwidth is 10 MHz.

This system includes circuits for acquisition and tracking of the frequencies from the moving user satellites. The rate of change of the doppler is preserved so that coherent range rate measurements can be obtained between the user and the earth station. The program is still in progress and the electrical performance is being evaluated at the present time (Reference 6). The characteristics of the channel modules are listed in Tables 2 and 3.

*The other information band is also fed to the same transmitting element through a diplexer (not shown in Figure 3).

Table 1

Characteristics of the Engineering Model

Parameter	Design Goals for Engineering Model	Measured Performance
Number of elements, each for two arrays	64	
Number of channels	2	
RF bandwidth, each channel	125 MHz	125 MHz
Guard band, between channels	100 MHz	100 MHz
Total cone angle of coverage	30 degrees	30 degrees
Element gain, minimum	11.6 db	12.4 db
Array gain, minimum	29.8 db	30.4 db
Polarization	Circular	Circular axial ratio = 0.8 db
Average mixer-filter preamplifier noise figure	15.2 db (max)	14.4 db
Effective radiated power per channel	28.0 dbw	27.8 dbw
Ratio of pilot to modulated signal power when 125-MHz bandwidth is utilized	-10 db	*
Attitude readout accuracy (min)	±0.5 degree	±0.5 degree
Power consumption: receiver	32.0 watts excluding LO	—
Power consumption: pilot processor	108.7 watts	182.6 watts
Power consumption: attitude readout	0.9 watt	—
Power consumption: total transmitter	201.1 watts excluding LO	87.9 watts** excluding LO
Prime power (exclusive of power supplies)	324.7 watts	270.5 watts
Total weight		180.0 kg

*Pilot signal ratios much lower than the design values were measured in the TV tests (see Reference 3).

**Power consumption applies to one channel of transmitter. For two-channel operation less than twice this value would be needed.

Table 2

IF Module†

Frequency	100 MHz
Number of beams	2
Data bandwidth	10 MHz
Pilot bandwidth	20 Hz
Weight	250 grams
DC power in	533 milliwatts

†See Reference 6.

Table 3

S-Band Module †

RF Module	Receive	Transmit
Frequency	2200-2300 MHz	1760-1840 MHz
Number of beams	unlimited	2
Noise figure	8.0 db	
RF power		60 milliwatts/beam
DC power in	2 watts	
Weight	210 grams	

†See Reference 6.

Multibeam Systems

Self-Steering Multibeam Repeater. A special configuration of a discretely-controlled multiple-beam array utilized Butler matrices (Reference 8) to form a high-gain antenna that received incident signals from arbitrary directions and processed them with amplification and frequency translation before re-radiating the signals toward selected directions (Reference 4). The system had two 4 × 4 arrays of helical elements, two beam-forming matrices (Reference 9), and two separate RF sections, one for transmitting at 4 GHz and one for receiving at 6 GHz. The cone of coverage for this system was 50 degrees. The principal feature of a 4 × 4 beam-forming matrix is the availability of 16 distinct beams or beam-pointing directions, any one of which can be selected by feeding energy into the appropriate beam port. The beams overlap to form in space the 4 × 4 cluster that is symmetric about broadside. The operation of the multiple-beam antenna system is described with reference to the schematic diagram of Figure 5.

The 6-GHz receiving system processed both the receiving and transmitting logic. Proper operation of the transmitting system required that the receiving and transmitting antenna beams be identical; the arrays and elements were scaled appropriately. The pilot signals were received by the 6-GHz array and its beam-forming matrix. The data signals from each beam port of the matrix were down-converted to IF. The pilot signals were passed to a 16 throw sampling switch whose output was directed to the input of one IF amplifier. Each pilot IF signal, after proper filtering at the output of the IF amplifier, was video detected and stored in sample-hold circuits, one for each beam port. These sample-hold circuits were synchronized with the 16 throw switch so that a particular sample-hold circuit then held the voltage of that particular channel until it was sampled again. The output of the sample-hold circuits are proportional to the power received by each antenna beam.

The function of the receiving logic was to determine the antenna beam with the largest receiving pilot signal and to switch the information channel into this beam by the application of a voltage to another 16 throw IF switch connected to the 10 MHz information channel. The amplified signal was then up-converted; the upper sideband was then passed to the input of the traveling-wave table (TWT) amplifier. The TWT amplifier raised the signal level up to that required for transmitting from the antenna system.

Because the constant-amplitude plane for each beam forms a circle, the gain will not be constant within the region of coverage. At points at which two adjacent overlapping beams are of equal gain, the gain is down ~4 db from the peak.

At points at which four adjacent overlapping beams are of equal gain, the antenna gain is down about 8 db from the peak gain. The use of distinct beams also gives rise to noticeable switching transients as the antenna system switches from one beam to another. To eliminate the effect of amplitude variations between adjacent beams and switching transients, the transmitting beam was continuously scanned. The distinct but overlapping beams were utilized to form one continuously moving beam. This improvement was accomplished by using four adjacent overlapping beams with appropriate weightings to form a new beam that continuously scanned to track the transmitting pilot. Although this scanning beam will have minor amplitude variations with scan, it will have no noticeable holes and also no noticeable switching transients.

The beam direction was controlled by digital ferrite switches and ferrite variable power dividers. With proper design only three power dividers and 12 SPDT digital switches were required for the scanning of one beam synthesized from 16 beams (Reference 10).

The self-steering multibeam arrays utilizing Butler matrices require logic circuitry (Reference 10) about as complex as that used for conventional phased arrays. However with "micromin circuitry," a significant reduction in weight and power consumption may be expected. Then the required logic for beam selection will find application in the future.

The concept can be extended to multiple independent channels with the use of additional electronics. Larger multibeam arrays with high-gain beams can be envisioned. Butler matrices, however, become more lossy as the number of beams increases. RF preamplification can be used on reception and post amplification on transmission to reduce RF losses. Alternate multiple beam systems can be considered such as multiple-beam feeds and lenses, which will be discussed next.

Variable-Coverage Communication Antenna

This antenna system is designed to provide a variable coverage on earth from synchronous altitude. Coverage can be varied from a 3-degree pencil beam to full-earth coverage. The satellite for this array will be stationary with three axis stabilization.

The system consists of a waveguide lens, a cluster of nineteen feeds and a switching matrix. A waveguide zoned lens of double-concave design with an F/D ratio of 1.0 was chosen (Reference 11). The feed cluster is a hexagonal array of conical horns, each having a 2-inch aperture and spaced 2 inches apart.

Figure 6 shows the lens antenna. The system operates at X-band with a total bandwidth of about 15 percent. Both senses of polarization are used, one for transmitting and one for receiving.

The directivity at the design frequency for the 19, 3-degree beamwidths is 31.5 db $\pm$ 1/2 db. The crossover level is 4.5 db between adjacent beams and 8 db at the point where three overlapping beams have equal gain. Earth coverage directivity with equal energy fed into all beams was 21.5 db with a peak to peak ripple of 2 db. All measurements are referred to the beam ports and do not include losses in the switching matrix or connecting networks. At the edge of the frequency band the gain is reduced by about 1 db for a scan angle of 7 beamwidths from broadside.

A corporate feed with variable power dividers is being designed (Figure 7). It will allow power to be divided among the 19 feeds in any desired ratio in order to provide for flexible beam shaping and transitions. Nonreciprocal ferrite phase shifters using a single ferrite slug will be employed (Figure 8). A separate network will be used for transmitting and receiving. The weight of the lens and feed system was 27 kg for the laboratory model. The flight model is expected to weigh 2-1/2 kg. These weights do not include the feed network and power divider.

Electronically Controlled Primary Feed For a 30 Foot Paraboloid

A multipurpose feed system is being developed for a 30 foot paraboloid which is part of the ATS-F* spacecraft (Figure 9). An S-band electronically scanned feed will be used for communications, and monopulse signal tracking. Cylindrical horns, a comparator, and a power divider comprise the elements of the system. Single-pole, seven-throw diode switches and circulators comprise the components of the S-band switching system. One set of four switches couple a signal being transmitted from the power divider through four circulators into the four selected feed horns. When a signal is received from a desired direction, the four horns forming a beam closest to that direction are coupled through four circulators to the comparator by a second set of four switches. A logic and switch driver circuit provides the proper switch diode bias states for independent receiving and transmitting beam positions. Beam position commands are received by the logic circuit from a remote command decoder.

One transmitting and one receiving beam are formed and can independently be scanned through a limited coverage area. Beamwidths are about 1 degree.

*NASA ATS F&G spacecraft series.

SPIN STABILIZED SPACECRAFT ANTENNAS

Spin stabilized spacecraft antenna requirements, with another major antenna technique category, are exemplified in the flight experience of the NASA Applications Technology Satellites (ATS), the Air Force Lincoln Laboratory Experimental Satellites (LES), and the Interim Defense Communication Satellite Program (IDCSP). These spinning spacecraft carry antennas that are electronically steered 360 degrees in one plane; the beam is counterspun and remains pointed towards the earth. The antenna systems have performed under operational flight conditions and the design techniques have thus been validated.

ATS-I, 4 GHz Array

Several despun arrays have been flown on the NASA ATS Satellites. The first one, a cylindrical transmitting array (ATS-I) operates at 4.1 to 4.2 GHz and consists of 16 elements spaced on a circle of one-wavelength radius (Reference 12). Each element of the circular array consists of a collinear array of half-wave dipoles. The power divider that feeds the phase shifters is a strip-line assembly and the coupling from the phase shifters to the linear arrays is also a strip-line assembly. Figure 10 shows the completed array. The array is fed by a power divider leading to eight ferrite phase shifters. Each phase shifter has two conjugate outputs to feed two diametrically opposite array elements. The phase shifter combines the properties of both the Fox and the synchronous ferrite phase shifter. To scan the array, varying currents are applied to each phase shifter. The currents are generated to cause a progressive phase shift around the array. This progressive phase shift causes the field to rotate under the control of a clock pulse that keeps the rotation of the RF field in synchronism with the spacecraft rotation. A sun sensor on the vehicle provides the reference for the control. Ground command can also be used.

The control electronics generates a set of 16 control voltages for the ferrite phase shifters. A system diagram is shown in Figure 11. The system uses a sun sensor as an input reference. A frequency-lock loop generates $2^9 = 512$ pulses for every input pulse. The output of the frequency-lock loop drives the beam positioner, which, in turn drives 16 sine wave generators in the proper phase to position the beam. The sine-wave generators drive output waveform generators and phase-shifter drivers which provide the required waveforms for the coils of the phase shifters.

The minimum array gain as measured on the spacecraft over the band is 13.5 db (Reference 13). This difference, compared with the directivity of 16.4 db is due to mismatches, shadowing of elements in the array, stripline losses, element matching network losses, and phase-shifter losses. Combined stripline and phase

shifter losses are between 1.5 and 2.0 db. Loss through a typical phase-shifter is about 1 db. This figure will vary over the range of operating temperatures by about ±1/4 to ±1/2 db, depending on the operating frequency. The weight and power consumption of the complete system are shown in Table 4.

Table 4

Characteristics of the ATS-I Despun Array
and Control Electronics

Weight of complete array as shown in Figure (9) (includes mounting structure to satellite that is not shown)	9.1 Kg
D. C. power into phase shifters (1/4 watt each)	2 Watts
Phase shifter drivers (Fig. 10)	
Weight	2 Kg
Power consumption (coil power of phase shifters excluded)	6.8 Watts
Number of electronic parts	828
Control Electronics (Fig. 10)	
Weight	2 Kg
Power consumption	4 Watts
Number of electronic parts	2064

ATS-III VHF Array

A VHF transmitting and receiving array was used as a repeater on the ATS-III (Reference 14). Eight whips deployed around the body of the spacecraft are used as the array. While the 4 GHz array on ATS-I utilizes a central (TWT) RF source and power divider, the VHF array is of the distributed type with every radiating element having its own receiver, transmitter, and phase shifter. The phase shifting is accomplished before final amplification. The repeater operates at 149 MHz for receiving and 136 MHz for transmitting. The antenna gain is about 7.5 db. Each phase shifter consists of an L-C delay line composed of seven cascaded L-C sections of a high-pass filter structure; variable delay is obtained by using varactors as the capacitive elements. The phase shifter is shown in Figure 12. The transmitter power is 7 dbw per element or 16 dbw into the eight element array.

LES-6 Despun UHF Arrays

Another technique uses a switched multiple beam array. It is being flown on two of the Lincoln Experimental Satellites (LES6). It operates at UHF, provides circular polarization, and consists of 8 slot pairs with concentrically mounted dipoles to obtain circular polarization (Reference 15). Upper and lower slots are fed in phase as collinear pairs.

The antenna system for LES-6 consists of two linearly polarized antenna arrays that are orthogonal to each other and fed appropriately to obtain circular polarization. The spacecraft is in the shape of a right circular cylinder, one wavelength (λ) in diameter and 1.3 λ high. The cylindrical portion of the spacecraft is covered with the usual solar cells. Advantage is taken of the gaps in the solar cells to place the circumferentially polarized slots which are about 0.5 λ long. Each slot is backed by a cavity 0.02 λ deep which consists of an inner-concentric cylinder divided into 16 cavities, one behind each slot. Dipoles of 0.4 λ for LES-6 were spaced about $\lambda/8$ from the cylindrical ground plane. The dipoles were located over the corresponding slots (Figure 13). As the spacecraft rotates, the beam, generated by two pairs of adjacent elements, is scanned in 22-1/2 degree steps, thus creating 16 beam positions. Two beam positions are obtained from each set at adjacent slot-dipole pairs by exciting them in two different phase relationships.

The feed network combines the transmitter beacon, receiver and radio frequency interference signals as shown in Figure 14. A detailed diagram of the switch matrix is shown in Figure 15. It is composed of two SP4T sections and a DPDT section. P-I-N diodes are used as the switches. The scan controller biases these diodes in the proper fashion so that the beam is scanned sequentially. The phasing and line lengths were optimized for the transmitting frequency. Table 5 summarizes the performance of the antenna. The gain is measured at the reference input as shown in Figure 14.

MILLIMETER WAVE COMMUNICATION ARRAYS

Future satellite requirements indicate that frequencies beyond 12 GHz will be employed in operating systems. Studies have been conducted to survey the state of the art and to come up with possible implementations (Reference 16).

The major components that need development include low noise front ends, efficient transmitters, and phase shifting devices. In conjunction with the aforementioned study, a digital ferrite phase shifter was developed at 35 GHz with an insertion loss of 1.5 db for 360-degree phase shift (Figure 16); a pulse of less than 20 milli-seconds with a drive power of 5 amps at 2 volts is required; the device weighed 59 grams with a size of 3/4 by 3/4 by 2-1/2 inches and a bandwidth

Table 5[†]

Despun-Antenna Gain (db) at Reference Input Shown in Figure 14

Frequency	East Edge of Earth	Center of Earth	West Edge of Earth
Transmit	+0.4 8.6 -0.3	+0.3 9.8 -0.4	+0.3 8.0 -0.4
Beacon	+0.3 +7.1 -0.2	+0.2 +8.4 -0.3	+0.5 +6.9 -0.4
Receive	+0.8 +8.5 -1.0	+0.3 +10.2 -0.3	+1.0 +8.3 -1.3

†See Reference 15.

of 3 percent (Westinghouse model WAX-35, April, 1967). Since then major efforts have been underway to improve the other components required for satellite systems operating at millimeter waves. Extensive work has been performed on multibeam electronically scanned lens systems at 35 GHz.

EARTH OBSERVATION INSTRUMENTATION

The application of electronic beam formation and steering to earth observation is illustrated by a planar array design that was qualified as a radiometric instrument at 19 GHz on jet aircraft and is now being qualified for spacecraft operation for the Nimbus D (Reference 17).

The antenna consists of a group of 49 parallel edge-slotted traveling arrays, each with 36 radiating slots. The aperture is 14 by 16 inches. The arrays and the feeds are of the nonresonant traveling-wave type. For scanning in one plane a set of analog ferrite phase shifters of the Spencer-Reggia type is used. Scan of ±50 degrees from broadside has been achieved; the beamwidth was 3 degrees, and gains of 32 to 36 db were achieved. Beam efficiencies of better than 90 percent were achieved;* the antenna losses were 1.0 db and the aperture efficiency

*Beam efficiency is defined as the ratio of the power in the main lobe to the total received power.

about 79 percent. The phase shifters had an insertion loss of about 0.6 db maximum. Input dc power was 62 watts for the total instrument, with about 20 watts for the antenna system (3/4 watt per phase shifter), and a 1/2 millisecond time between beam position. The overall system noise figure was 6.0 to 7.0 db; accuracy was 2.0°K with a 0.7 degree sensitivity for the radiometer. The bandwidth was 300 MHz. A photograph of the array is shown in Figure 17. A second planar array with twice the physical aperture is in development for NASA Nimbus E. Figure 18 shows a sketch of both arrays (Reference 18). A third design allows a radiometer receiver and a short-pulse radar to share the same antenna system as an Earth Resources Spacecraft Sensor at 19 GHz (Reference 19).

The aperture control technique is extendable for operation over the entire 0.1 to 35-GHz microwave region from a one dimensional scan to two dimensional scanning.

RADAR

A laboratory breadboard array of 16 elements has been fabricated and tested for application to a NASA Manned Spacecraft rendezvous radar. The 6 GHz array was designed to scan ±45 degrees in two dimensions (Reference 20).

The novel feature was the all solid state C-band transmit/receive module. It used as a phase shifter a step recovery diode (SRD). The bias of the diode is adjusted to obtain a limited amount of phase shift. Since the output of the diode is rich in harmonics, the output is tuned to a harmonic of the input frequency, giving an automatic multiplication of the phase shift. In the receiving portion a multiplication of eight times was used. Linearity between phase shift and applied voltage was good. The output signal (4 milliwatts) from the phase shifter serves as the local oscillator for the mixer. In the transmitter, the multiplication in the SRD phase shifter is two. Further multiplication by a factor of five is achieved by a fixed-bias SRD. Pulsed output power was 300 mw/module with a duty cycle of 0.005. A photograph is shown in Figure 19.

THE FUTURE OF SPACECRAFT PHASED ARRAYS

It becomes fairly evident that there are many applications for which electronically steered arrays are the best solution for present and future missions. The technology for these arrays is evolving rapidly. However, several critical areas

must be resolved before their full potential can be realized. These are discussed as follows:

a) Electronically steerable antenna systems must be considered not only on the basis of an antenna aperture but on the basis of a communications system that embraces a complete receiving system as well as transmitter, modulator, frequency converter and power amplifiers. These systems have already been shown to be competitive with the noise figures, stability, bandwidth, dispersion qualities, and reliability of the discrete subsystems, receivers, modulators, and transmitters.

b) The continuous upgrading and application of microcircuits to the fabrication of the multiple channels of the electronically steerable antenna designs must produce systems of weight and power consumptions competitive with the discrete subsystems—provided that comparisons are made on a total performance level.

c) The continual frequency increases for operation at millimeter wavelengths is dependent on reduction of mixer noise figures, transmitter efficiency upgrading, frequency stabilities, and low insertion losses for all subsystem components. A better understanding of the propagation losses due to rain must also be obtained for operational systems.

d) The demonstration of a total reliability figure for operation in a spacecraft environment is a critical development task.

e) Other aspects in the overall system design must include the consideration of the forward scatter or multipath problems that will be encountered (Reference 21). Solutions have been proposed using antenna techniques, electronic processing techniques, and modulation techniques such as spread-spectrum (References 21 and 22). The problem of the capture of the channel by the multipath signal in self-steering systems has been investigated and several solutions have been proposed. However, the quantitative nature of the forward scatter for surfaces such as the ocean needs further investigation before several of the techniques can be applied with certainty (Reference 23).

CONCLUSIONS

This review indicates that the basic principles and techniques of electronic steering have been demonstrated to conclusive levels, in both the laboratory developmental models and in spacecraft flights, for communications and survey instrumentation applications.

Spacecraft carrying electronically despun beam steering systems under operational flight conditions have validated the design techniques, and have been flight qualified for as long as three years. What needs to be done now is to apply the best of microminiaturization technology to circuitry, components, and solid state devices in order to provide spacecraft antenna systems that are of operational quality, and also, that can perform tasks which are infeasible by mechanically-actuated antenna systems.

REFERENCES

1. Sichelstiel, B. A., Waters, W. M., and Wild, J. A., "Self-Focusing Array Research Model, " IEEE Trans. Antennas and Propagation, Vol. AP-12, pp. 150-154, March 1964.

2. Pon, C. Y., "Retrodirective Array Using the Heterodyne Technique," IEEE Trans. Antennas and Propagation, Vol. AP-12, pp. 176-180, March 1964.

3. Kummer, W. H., and Birgenheier, R. A., "A High-Gain Self-Steering Microwave Array," Proc. IEEE, Vol. 56, pp. 2028-2038, November 1968.

4. Kummer, W. H., and Villeneuve, A. T., "Spacecraft Antenna Systems, Phase I," Final Report, P65-35, NASA/Goddard Space Flight Center Contract, NAS 5-3545, pp. 145-166, January 1965.

5. Seaton, A. F., and Birgenheier, R. A., Unpublished Work, Hughes Aircraft Company, Culver City, May 1968.

6. Schwartz, L, Smith, J., Popovich, B., and Dod, L. R., "Data Relay Satellite Phased Array," AIAA Paper 70-424, April 1970.

7. Birgenheier, R. A., and Sisson, A. R., "A High-Gain Self-Steering Microwave Repeater," Final Engineering Report, Vol. II, NASA/GSFC Contract NAS 5-10101, Report No. P69-403, September 1969.

8. Butler, J., and Lowe, R., "Beam Forming Matrix Simplifies Design of Electronically Scanned Antennas," Electronic Design, Vol. 9, pp. 170-173, 1961.

9. Kummer, W. H., "Self-Steering Arrays for Satellite Applications," Communication Satellite Systems Technology, Progress in Astronautics and Aeronautics, No. 19, Marsten, R. B., Ed., New York: Academic Press, pp. 573-592, 1966.

10. Kummer, W. H., and Birgenheier, R. A., "Spacecraft Antenna Systems," Final Engineering Report, NASA/GSFC Contract NAS 5-3545, Report P66-66, March 1966.

11. Dion, A. R., "Variable Coverage Communications Antenna for LES-7," AIAA Paper 70-423, April 1970.

12. Erhardt, H.R., Gerson, A., and Mead, D. P., "The Advanced Syncom Communication Antenna System: A Directive Array for Spin Stabilized Satellites," IRE National Symposium on Space Electronics and Telemetry Record, 1963.

13. Phased Array Transmitting Antenna and PACE, NASA/GSFC Contract NAS 5-3823, October 1966, also HAC Document SSD 60196R.

14. VHF Repeater Experiment for ATS/C, NASA/GSFC Contract NAS 5-10290, HAC Report P67-56, February 1967.

15. Rosenthal, M. L., Devane, M. E., LaPage, B. F., "VHF Antenna Systems for Spin-Stabilized Satellites," Trans. IEEE, AP-17, pp. 433-451, July 1969.

16. Study Program on 30-100 GHz Electronically Steerable Antenna Systems, ADTEC, NASA/GSFC Contract NAS 5-10256.

17. Louapre, M. E., and Fujioka, J. K., "A High-Efficiency Electronically Scanned K-Band Phased Array for Spaceborne Radiometric Applications," Proc. IEEE, Vol. 56, pp. 2010-2016, November 1968.

18. NASA/GSFC Contract 5-2115 with Microwave Division of Aerojet General, El Monte, California.

19. Kampinsky, A., Proposal: "Combined Radar/Radiometer System Sharing a Common Antenna," NASA/GSFC, April 1966.

20. "Engineering Model of an Electronically Scanned Phased Array Antenna System," Final Report, Ryan Company, Report No. 59867-1, NASA/MSC Contract NAS 9-7626, May 1969.

21. Durrani, S. H., and Staras, H., "Multipath Problems in Communications Between Low-Altitude Spacecraft and Stationary Satellites," RCA Review, pp. 77-105, March 1968.

22. LAS/DRSS Multipath Transmission Study, NASA/GSFC Contract NAS 5-11602, Hughes Aircraft Company, 1970 (to be issued).

23. Kummer, W. H., Villeneuve, A. T., and Weiner, K. R., "Literature Review for the Multipath Study of a Low-Altitude Satellite Utilizing a Data Relay Satellite System," NASA/GSFC Contract NAS 5-11602, June 1969.

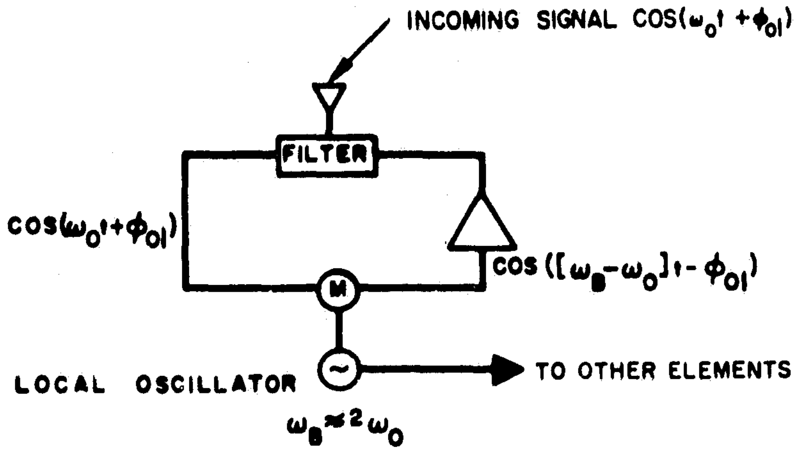

Figure 1. Elementary Array Module

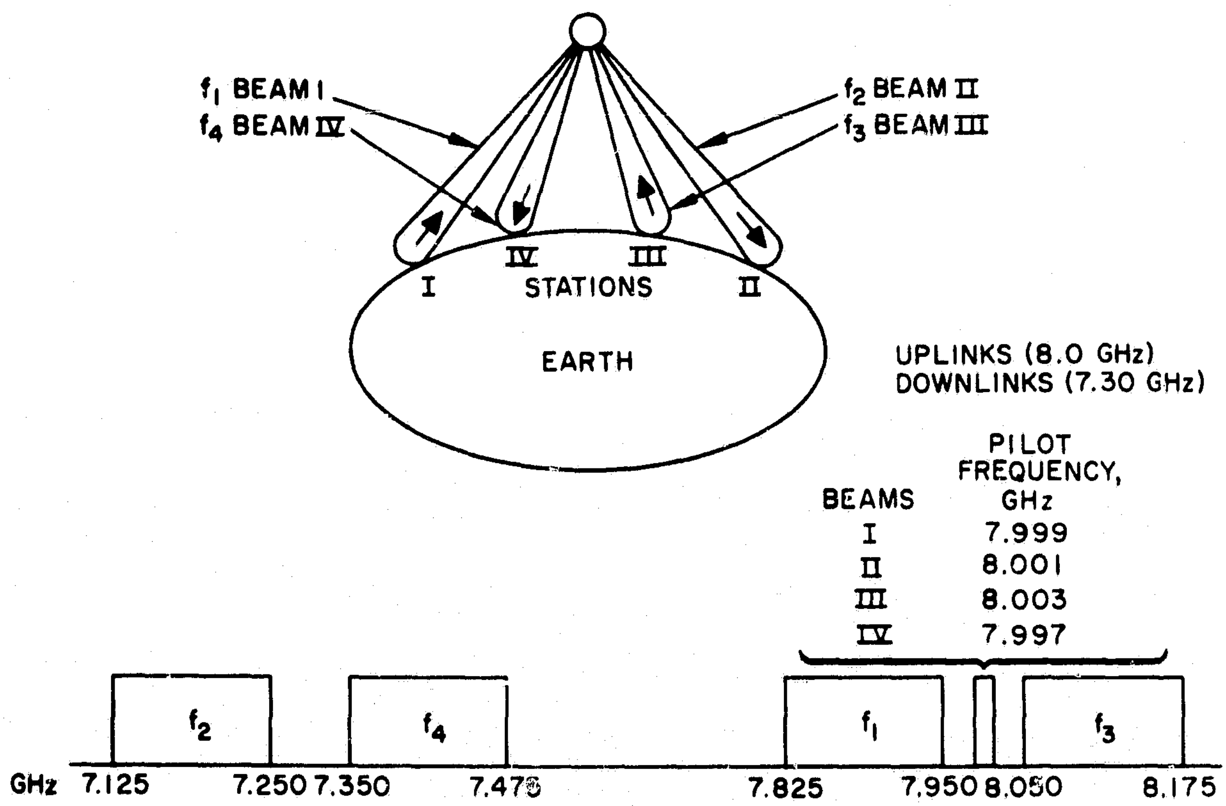

Figure 2. Beam Desginations and Frequency Bands
Utilized by the Self-steering Repeater

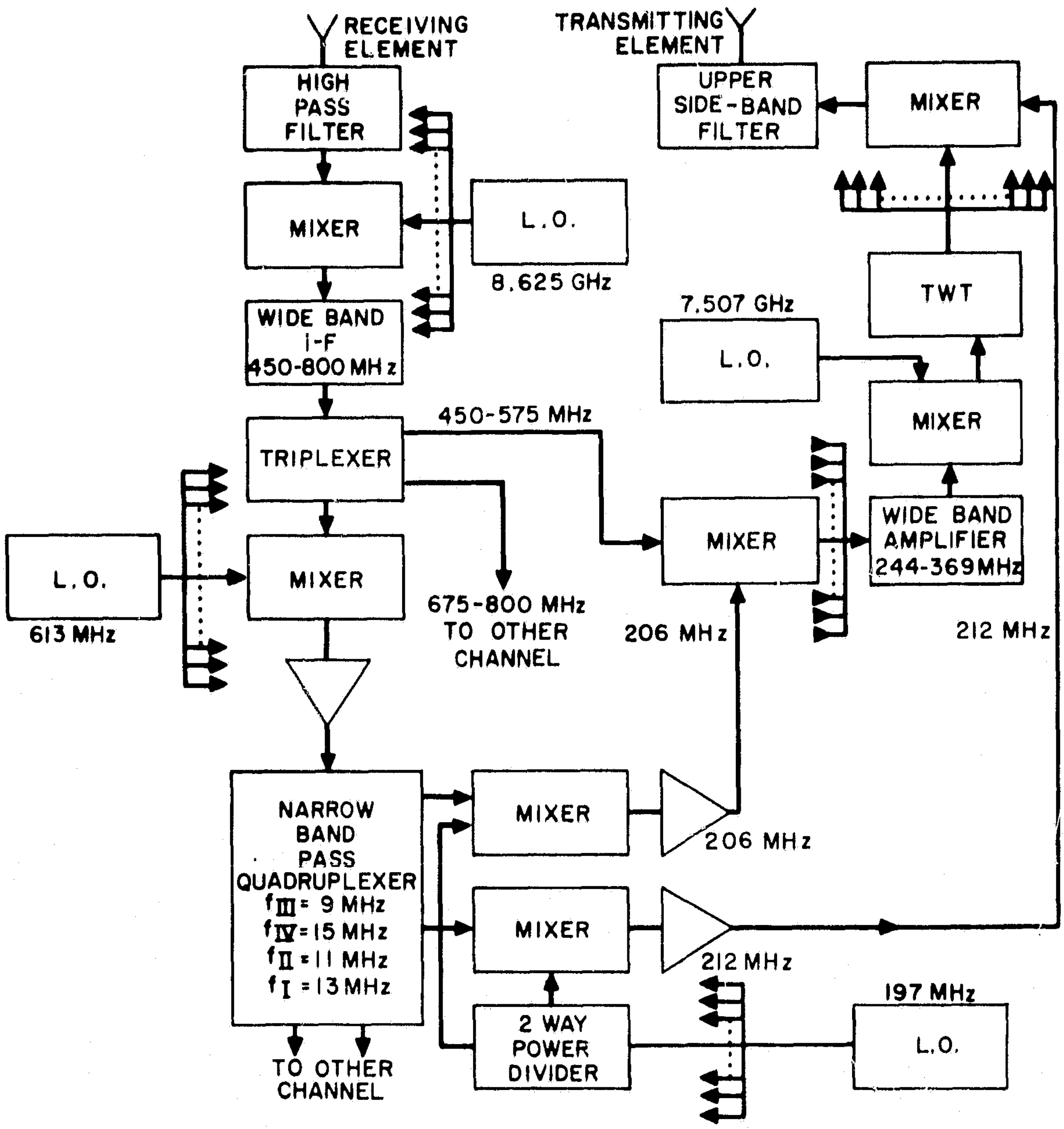

Figure 3. High-gain Self-steering Engineering Model Schematic (The subscripts of the pilot frequencies correspond to the beams shown in Figure 2)

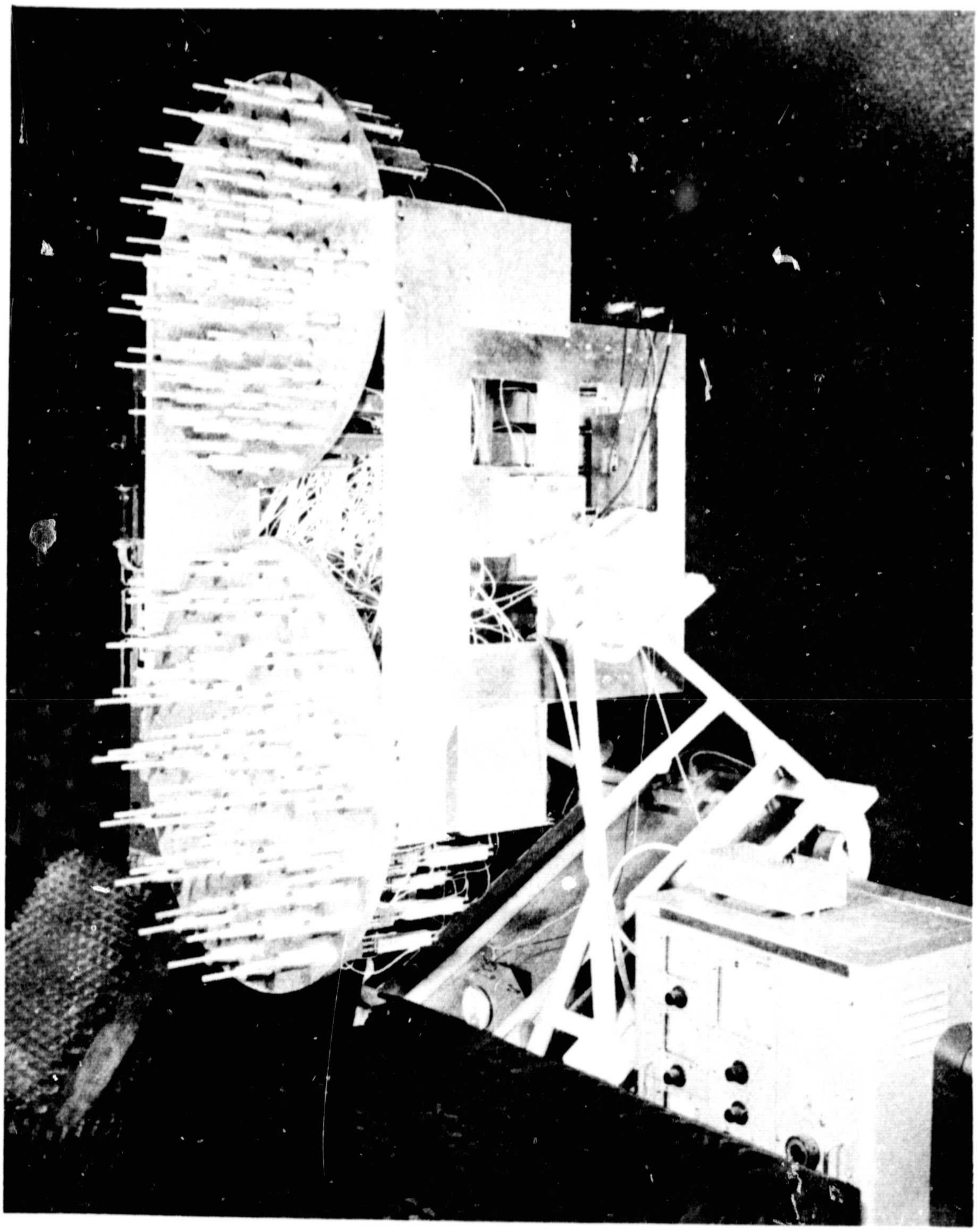

Figure 4. Complete Repeater

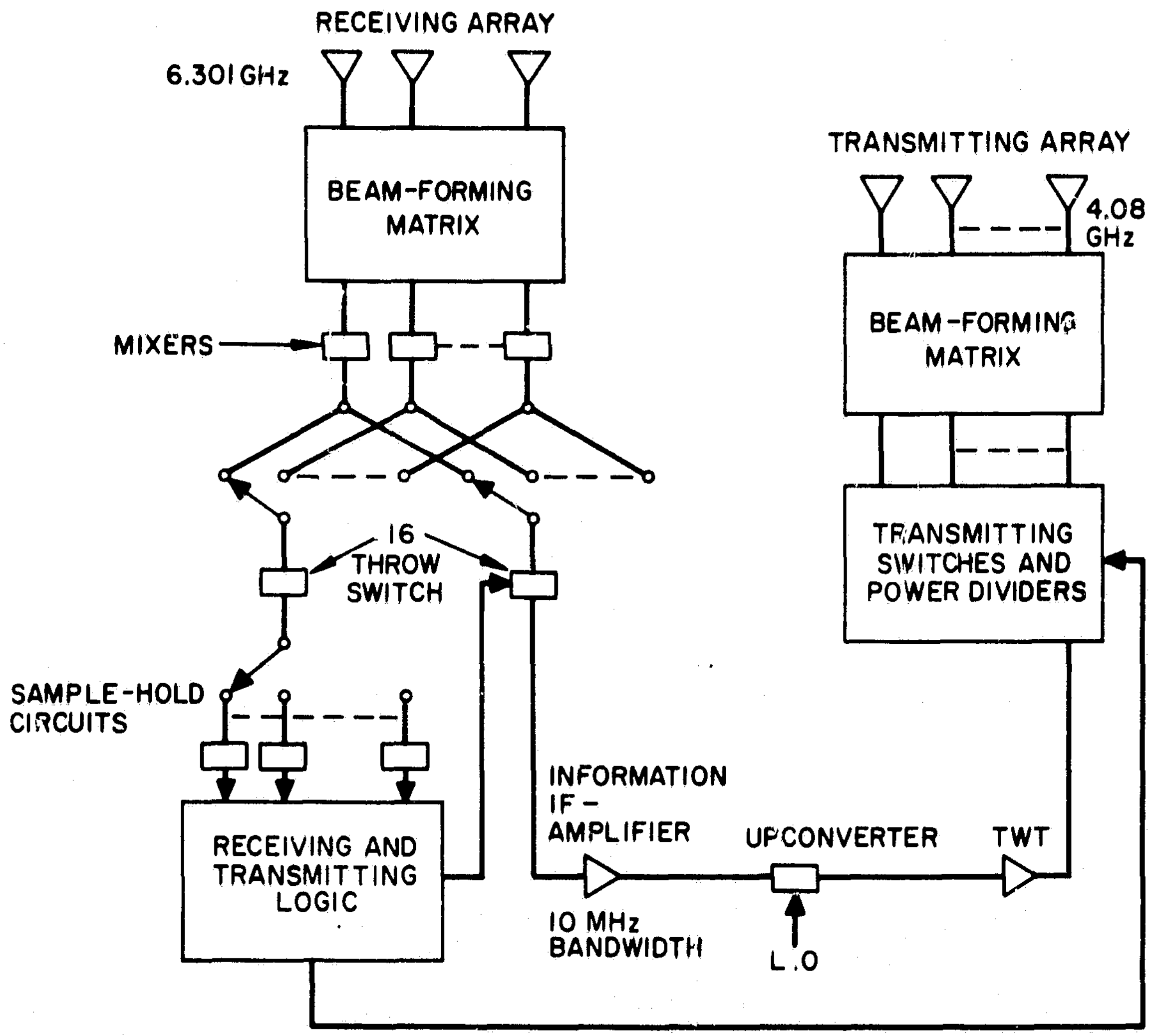

Figure 5. Multiple-beam Antenna System Schematic

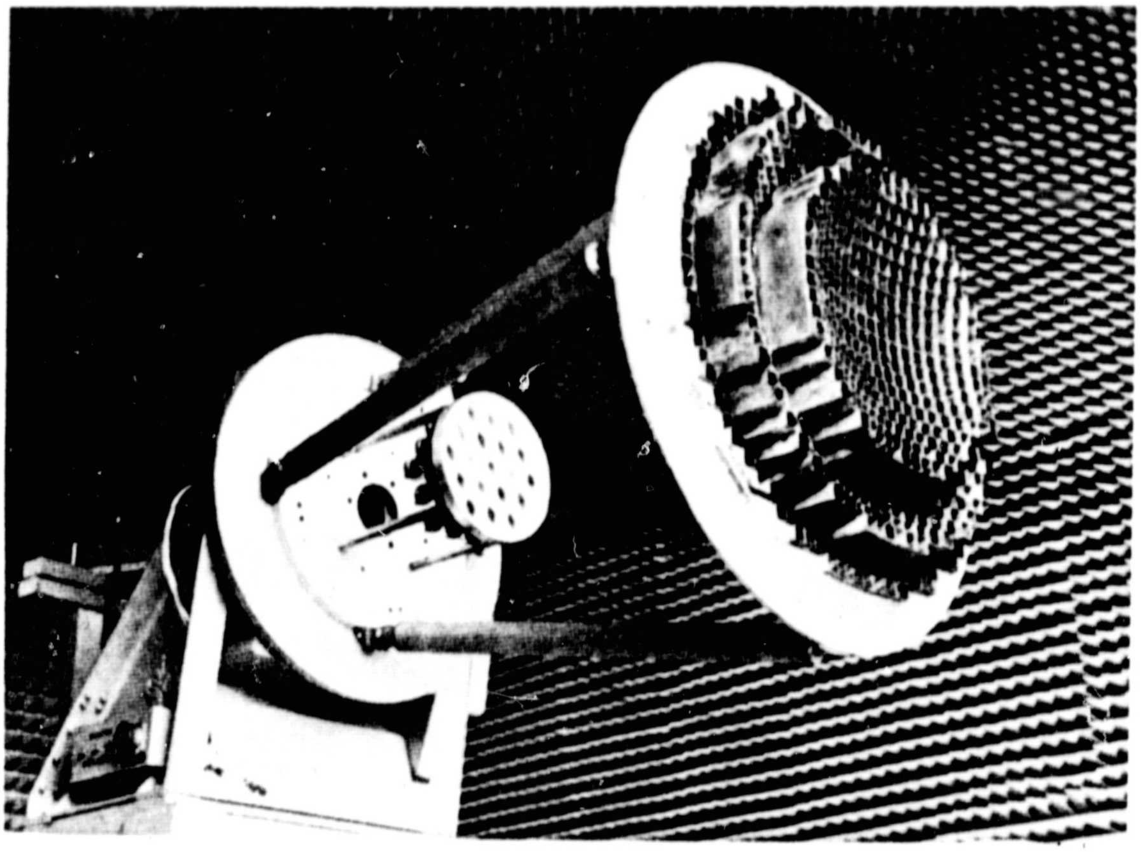

Figure 6. Experimental Lens Antenna (Reference II)

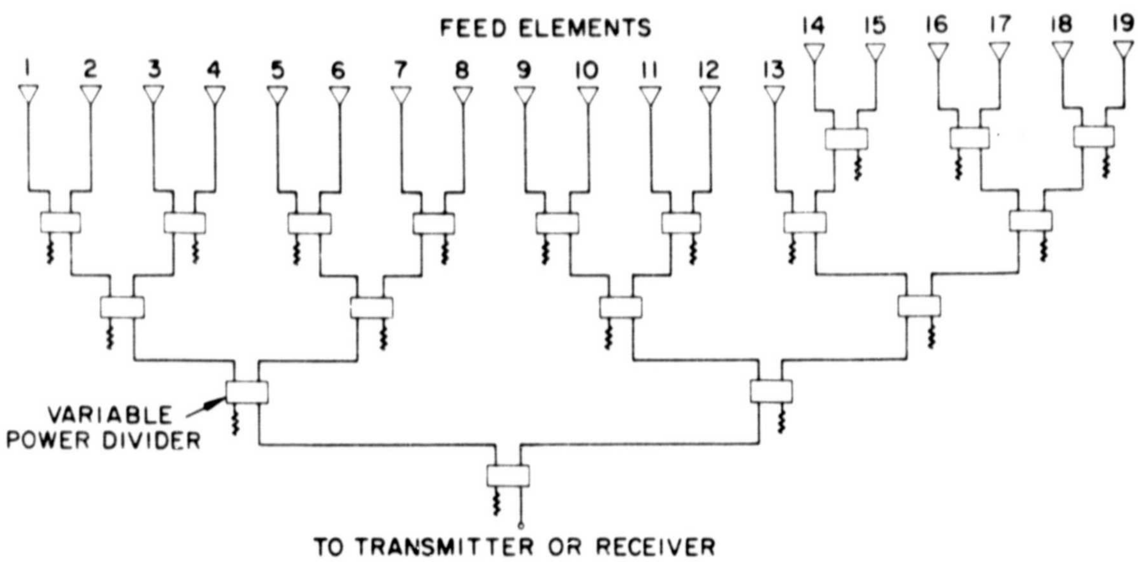

Figure 7. Proposed Combiner Switch

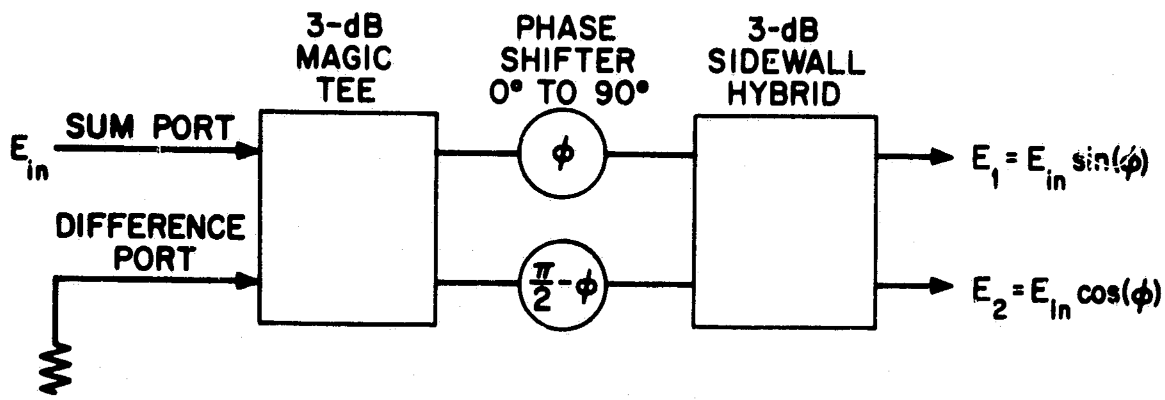

Figure 8. Power Divider

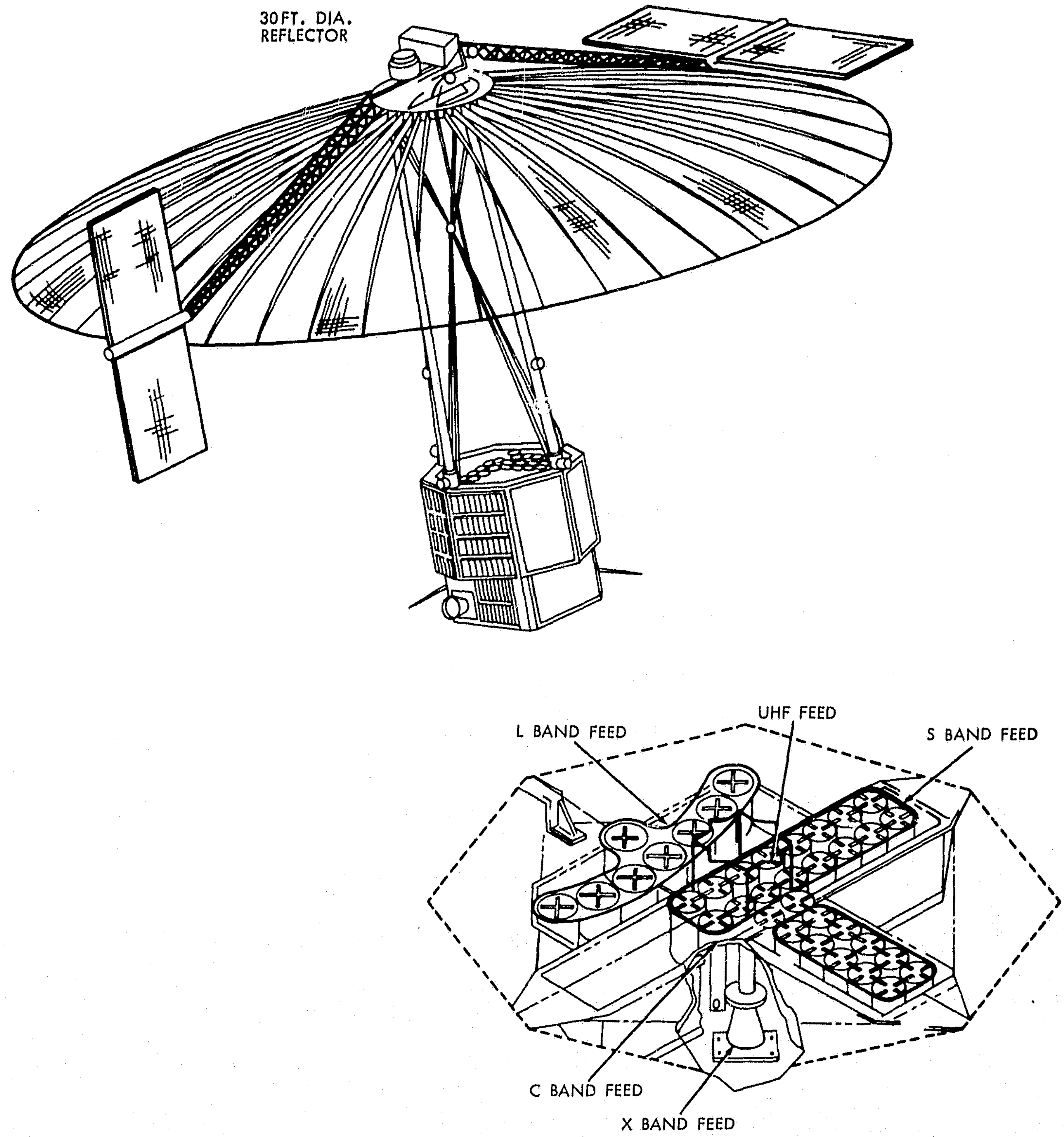

Figure 9. Primary Feed Array Used on the ATS-F and -G

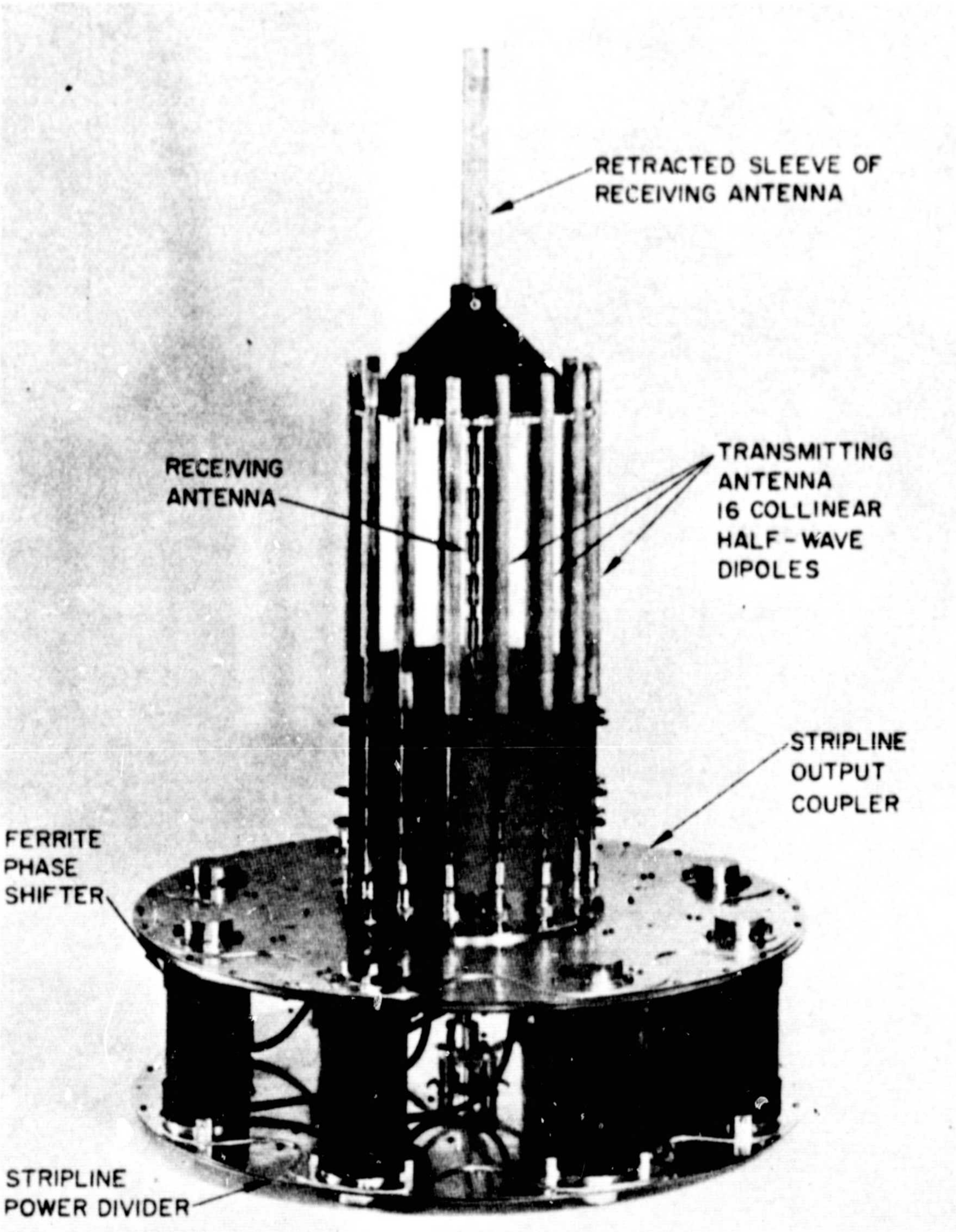

Figure 10. Applications Technology Satelite I Circular Phased Array

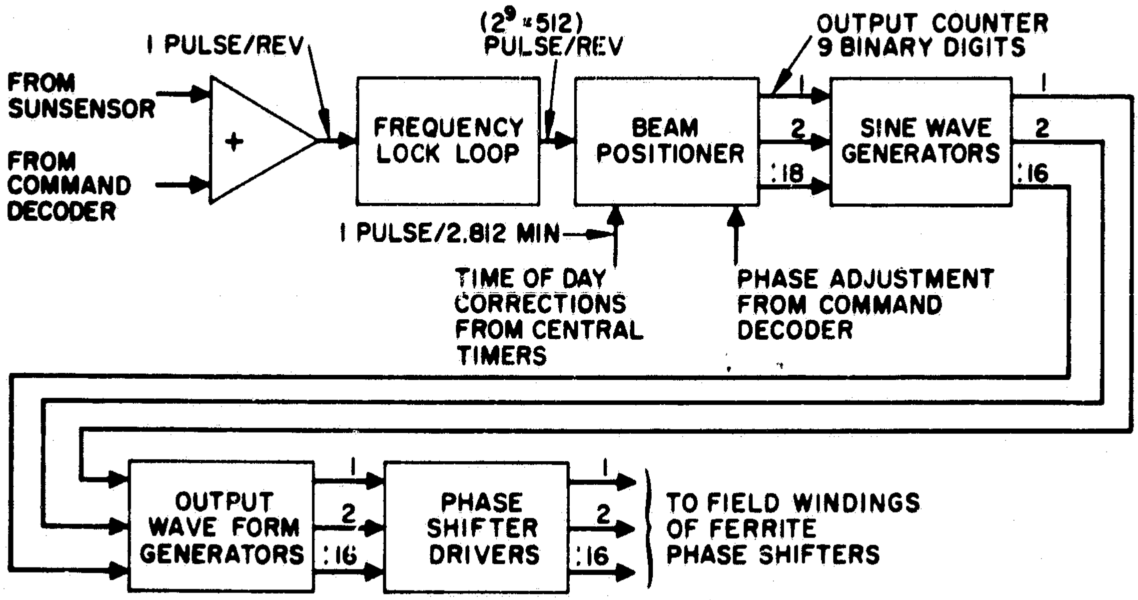

Figure 11. System Diagram of Control Electronics for Circular Phased Array

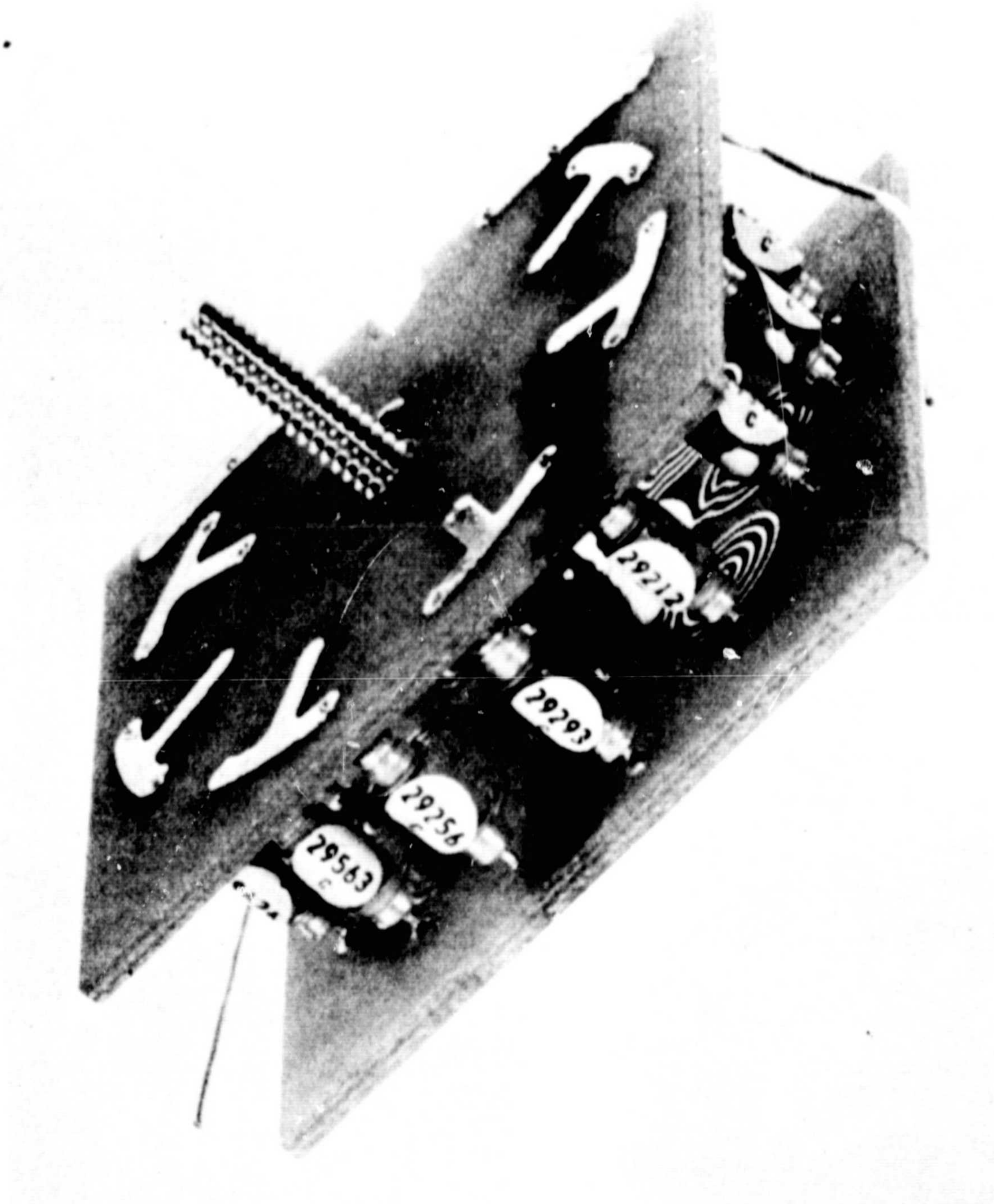

Figure 12. Phase Shifter Using Helical Printed Circuit Conductors

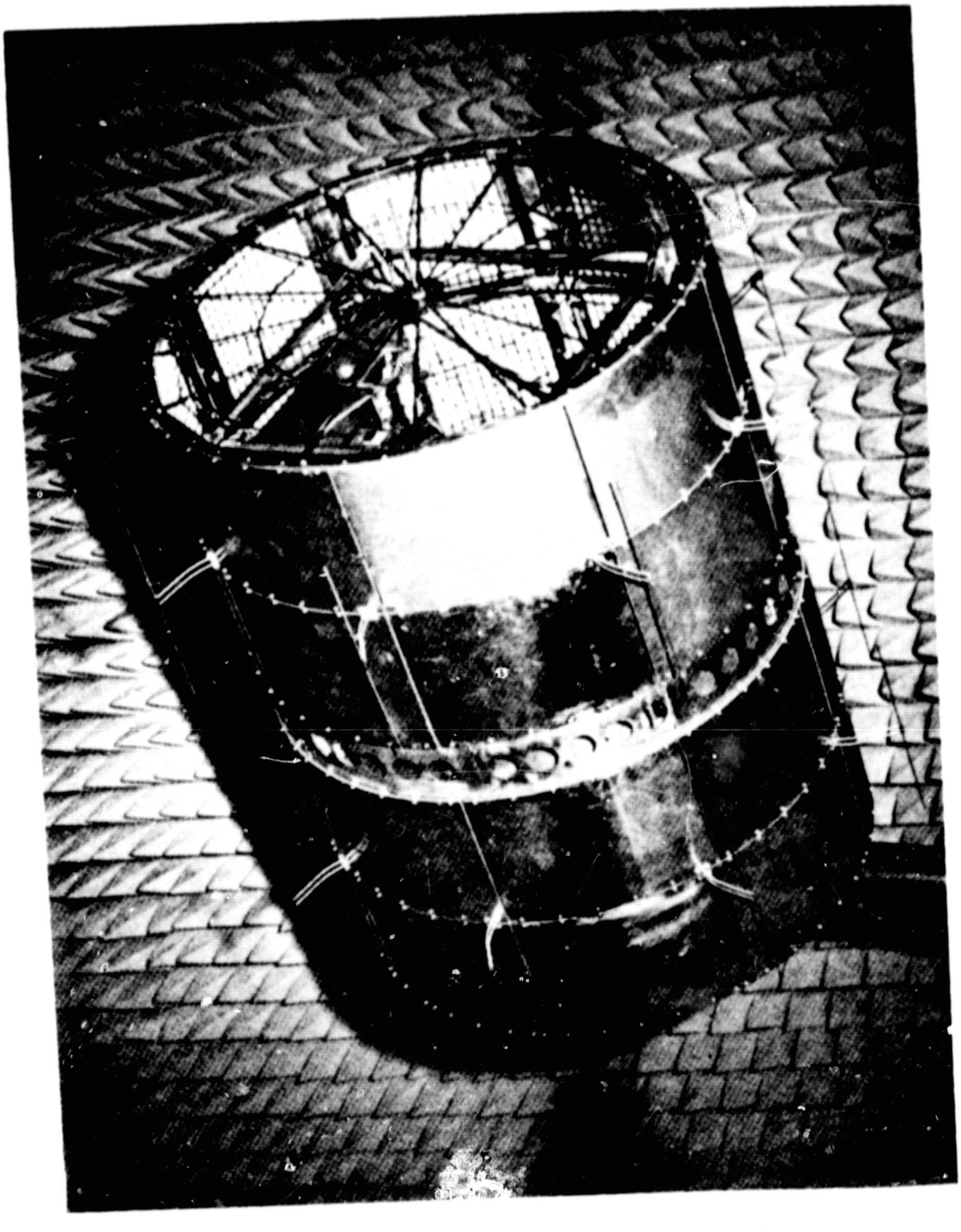

Figure 13. Details of Slot-dipole Array for LES-6 Spacecraft

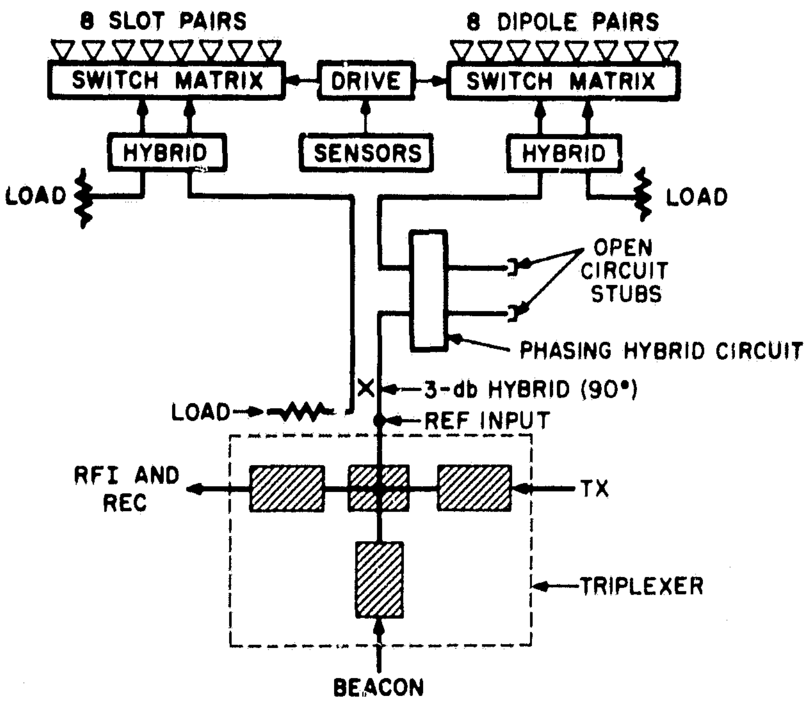

Figure 14. Despun-antenna System

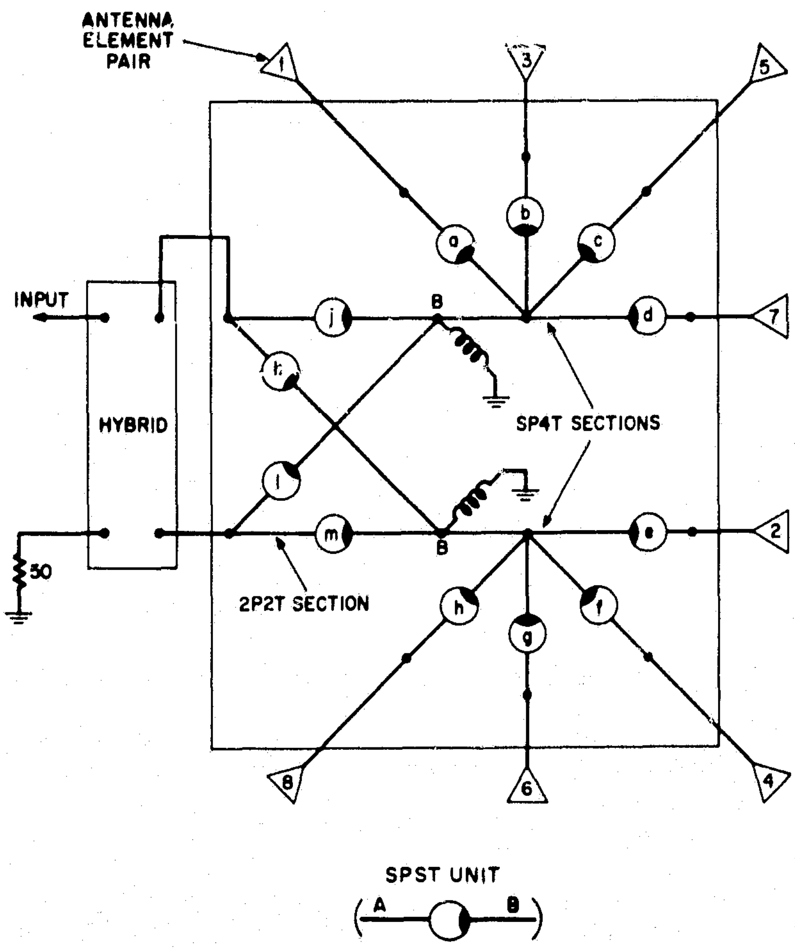

Figure 15. Switch Matrix

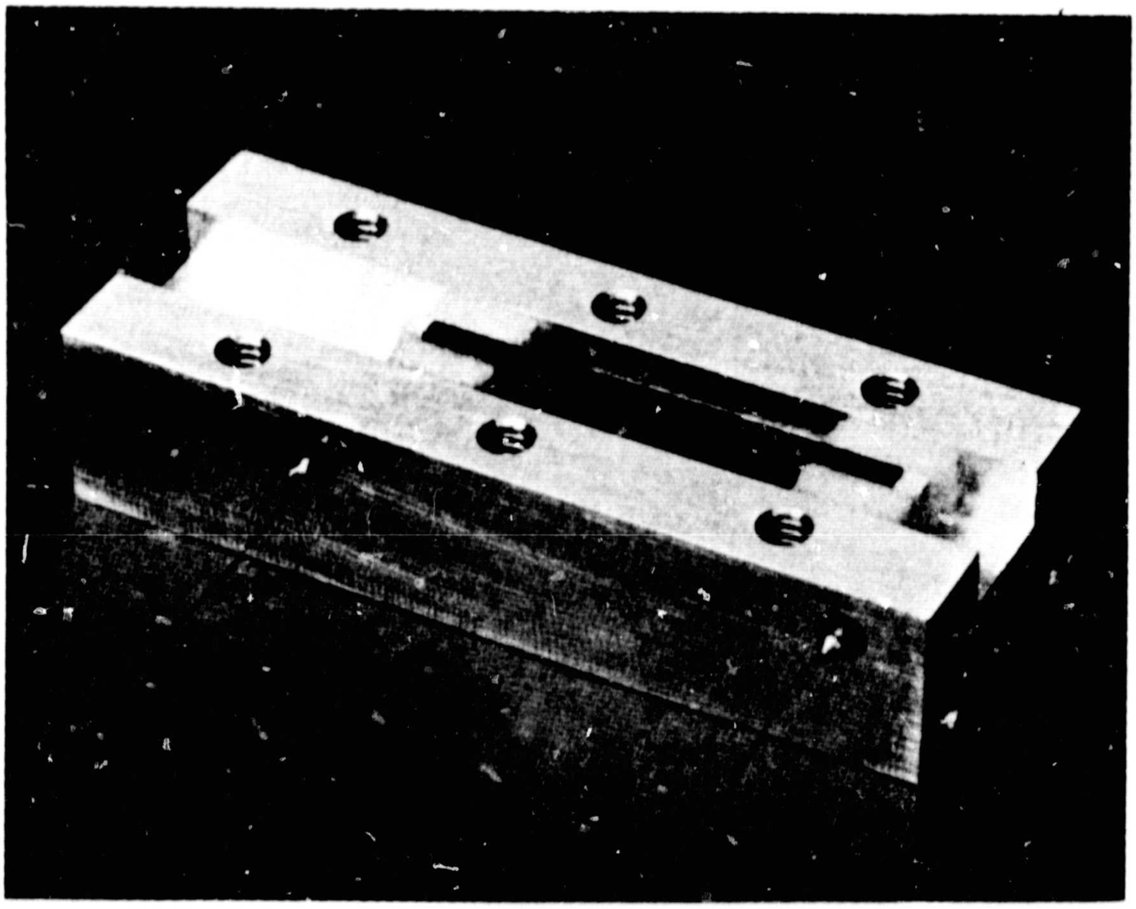

Figure 16. Westinghouse 35 GHz Phase Shifter

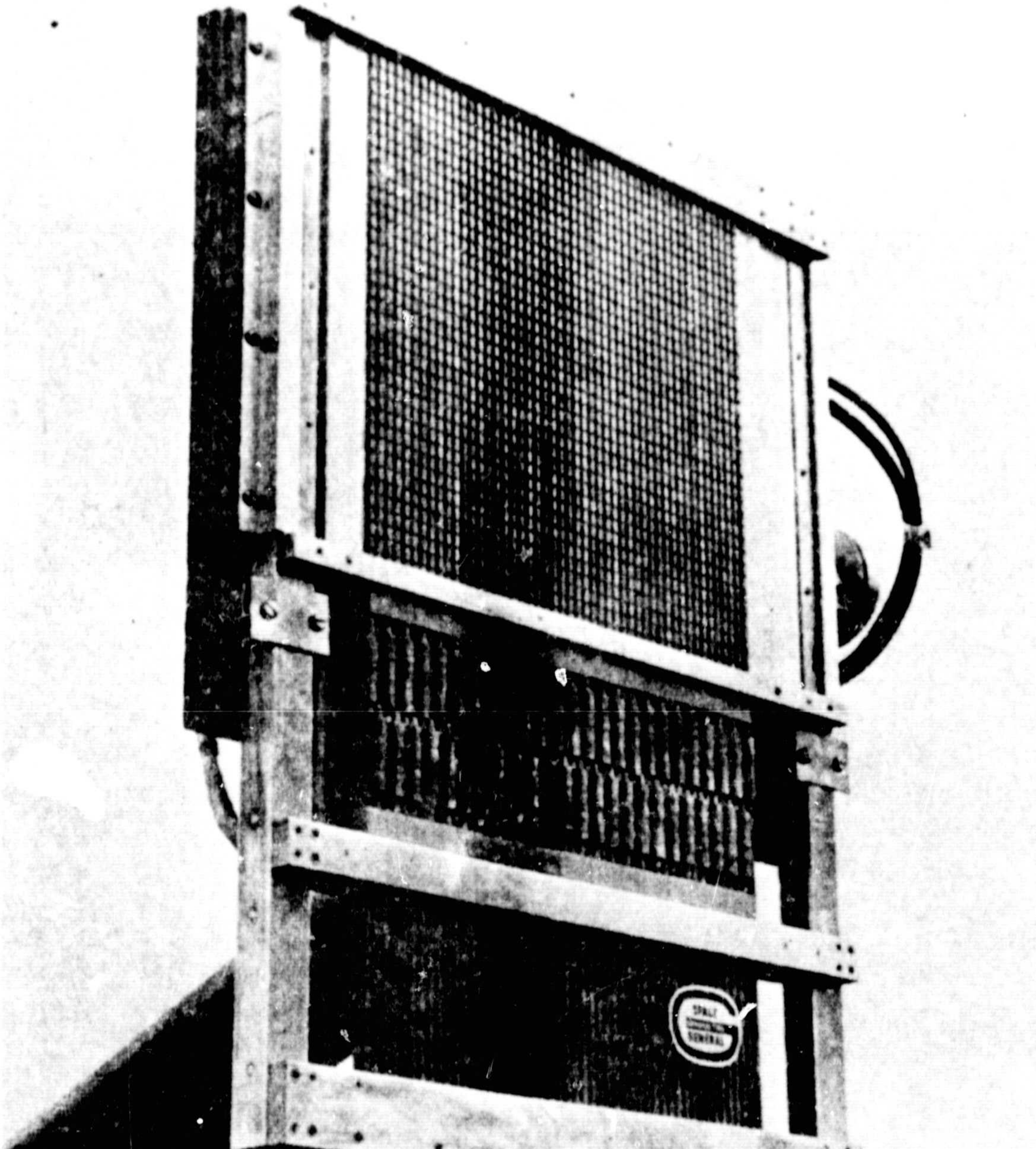

Figure 17. Electronically Scanned Planar Phased Array

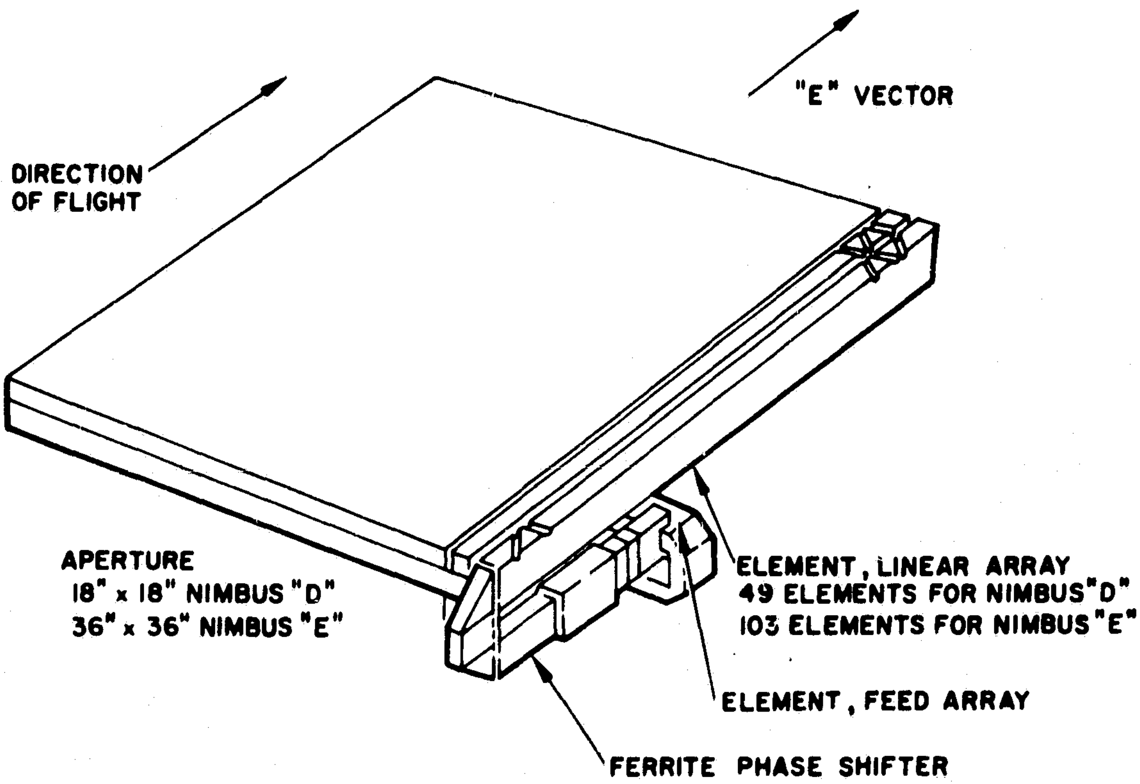

Figure 18. Electronic-scanning Radiometer 19.35 GHz Antenna System

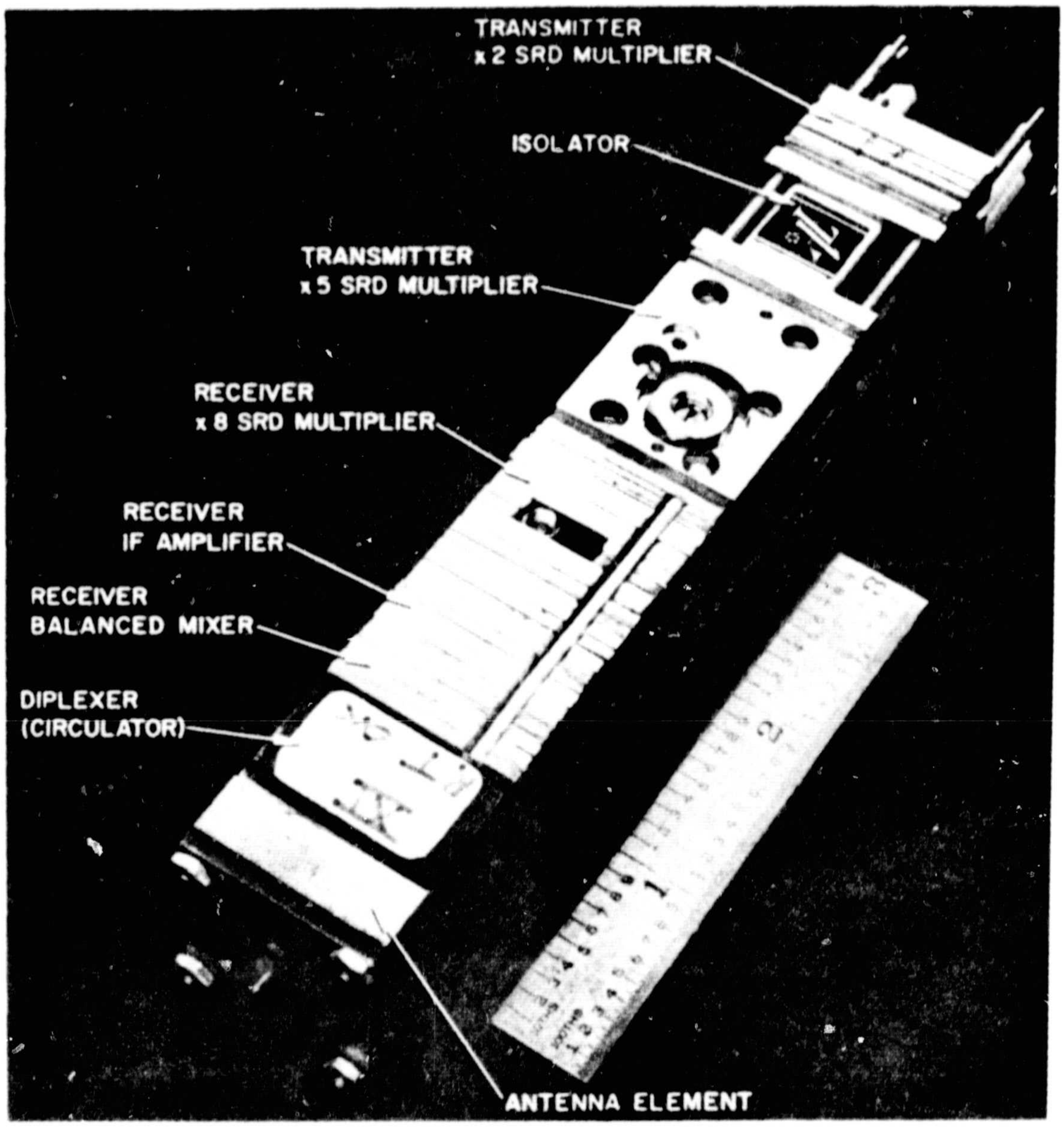

Figure 19. Assembled C-band Transmitting/Receiving Module